Adaptive hierarchical power control of renewable generation with HVDC transmission facilitated by hundred megawatts battery energy storage station

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***Abstract*—Battery Energy Storage Station (BESS) is the most effective way to facilitate transmission of large scale hybrid power generation that includes unpredictable renewable energy sources. In this paper we consider a wind-solar-thermal power system with HVDC transmission facilitated by BESS. This paper proposes a three-hierarchical power imbalance regulation method. In the first hierarchy, an adaptive based PI controller is used to regulate frequency deviation. Then according to cooperative game model the distributed power adjustment orders are decided in the second hierarchy. The last level the weight factor distribution strategy, which includes two designed mechanisms for the both two alliances. We exam the impact of proposed three-hierarchical power control strategy through a simulation model. The performance evaluation demonstrates its validation and thus it provides useful insight for designing hierarchical adaptive game schemes for the hybrid power system with HVDC transmission.**

Keywords—Renewable Power; Battery Energy Storage; HVDC Transmission; Adaptive hierarchical control; Game Theory

I. Introduction

Renewable energy especially wind power and PV power have been rapidly developed since the environment issue caused by fossil fuel consumption is intensified. Since 2011 China has been the country with largest installed wind power capacity, and the wind power capacity continues increasing significantly every year[1]. China also ranked first in photovoltaic generation in 2015[2]. But the regions with the most resourceful renewable power locate far from the load center. At present, accommodation capability of wind power in Northwest, Northeast and North China tends to be saturated. With the planned integration of large-scale photovoltaic power, it is urgent to transmit redundant renewable power to loads of other regions. Increasing renewable energy utility most important way to increase energy efficiency, which is essential to help reduce greenhouse gas emission and global warming[3]. The feasibility of transmitting large-scale renewable power located in Northeast and Northwest to North, East and Central China grid through high voltage direct current (HVDC) projects was systematically researched[4]. In order to successfully transmit large-scale renewable energy through LCC-HVDC system, at sending end the thermal power plants are built to provide voltage support[5]. Thus, formed a wind-solar-thermal bundled power sending system.

However, the intermittent renewable power can cause serious power imbalance in the sending end. To ensure power system operate stably, the most likely choice is to curtail wind power. China had the most serious wind power curtailment in recent years. In 2015, the annual abandoned wind power was 33.9 billion kwh, and the average rate of abandoned wind was 15% [6]. Northwestern China is the area that holds most rich wind power resource but also suffer the most serious wind power curtailment. Gansu province discarded wind power 8.2 billion kWh and the wind curtailment rate was as high as 39% last year. One reason is that the regional power grid is relative weak, which means lacking of enough peak shifting ability. Another important reason for the large amount of wind curtailment is lacking of cooperation among the sub-generation systems.

The power imbalance caused by uncertain renewable power is still highlight research issue. [7] presented the method for calculation of maximum wind power penetration in an island power system with VSC-HVDC or LCC-HVDC, but it didn't propose specific control strategy to inhibit power imbalance. Some work focused on transient stability study. [8] made the initial high-frequency generator tripping strategy adaptive to different faults for wind-PV-thermal transmitted by AC/DC system. The operating characteristics of HVDC, the operational conditions of both grid-connecting and islanding modes in the transition period and the imbalanced power distribution in weak sending end network is studied in [9]. Some research is mainly about power and voltage control. [10] has proposed an DC power modulation strategy which uses wind farm power as input. [11] exploit distributed solar energy and P2P technologies to aggregate distributed computing resources to provide solar-based energy-efficient distributed server farm for distributed computing and distributed storage. [12] also proposed an additional control strategy to the UHVDC system, which changes the power or current order according to the variation of system frequency. Energy Storage has been widely used in low-voltage level and it proved to be effective[13]. As the decreasing cost and increasing security of battery-based energy storage technology, it become more and more popular in smarter grid technologies with industrial-grade reliability[14-15]. In micro-grid,

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energy storage has been widely used and proved to be very effective in regulating power fluctuation. Most researches on large-scale renewable power HVDC transmission didn't consider BESS to facilitate stable operation at sending end. Since the power batteries price keeps decreasing, applying BESS to hybrid power generation with HVDC out-sending is possible [16].

This paper considered not only adding BESS but also HVDC additional control to facilitate frequency regulation. This hybrid system is complicated since the integration of distributed renewable generations, battery energy storage station and HVDC. This paper proposes an adaptive hierarchical power control model. The hierarchical multi-objective system can function feasibly and coordinately under appropriate design[17].

This model has three control levels:

- At the first level the parameters of the PI controller will be adaptively updated according to renewable power prediction. We use 120 minutes as the time interval of adaptive learning updating.
- In the second level, we need to deal with the challenge of finding optimal strategy for each agent such as to make balance and optimize benefits of every subject in power system. The traditional single decision making based optimization system hardly resolve this problem. As a promising method for multiple objects optimization, game theory has been applied to deal with this challenge[18]. The power adjustment weight factors are distributed to two game alliances.
- In the bottom level, the dynamic weight factor distribution strategies among each alliance. For the renewable generation alliance, the operating capacity ratio is the principle determinant element; The thermal power, BESS and HVDC make up of another alliance. When fixed thermal power adjustment ratio, BESS and HVDC weight factors distribution are based on operation cost and regulating effects.

The adaptive PI control strategy in the first hierarchy, sending down the dynamic power adjustment order to each subsystem alliances, will not only have better frequency performance than constant PI control strategy but also enable the BESS to have a better state of charge (SOC) range. The game theory model in the second hierarchy determines alliances power adjustment ratio from the perspective of global optimization. At the bottom level, weight factors distribution is based on characteristic of each subsystem. To verify the three-hierarchy control strategy will be effective, we build a simulation model under selected alliance weight factor distribution case. To demonstrate the advantage of adaptive control strategy, simulation for both adaptive PI control and no-adaptive PI control are made to make a comparison.

II. SYSTEM MODEL

A. Problem Formation

We consider an electric power system which consists of wind farms, PV station, thermal generation units, BESS and HVDC transmission as shown in Fig. 1. Each thermal unit is equipped with thermal generator control system (TGCS); each wind farm is equipped with wind farm control system (WFCS); each PV station is equipped with photovoltaic control system (PVCS); HVDC transmission system is added the DC control system (DCCS); the BESS is also equipped with battery control system (BCS).

This paper the entire scheduling interval (e.g. 2 hours) is divided into T time-slots with equal duration, whose set is denoted by $\tau = (1,2,\cdots T)$ (e.g. T=120 time-slots). We assume that the power scheduling is determined at the beginning of the entire scheduling interval. The output power of thermal generation unit i and renewable generation unit during time slot t is denoted by the variable $P_{iT}(t)$, $P_{jW}(t)$ and $P_{kP}(t)$. Compared with thermal and renewable power generation, BESS is capable of charging and discharging energy in/from the batteries. As we define energy inputting into BESS as positive, the power consumption of BESS at time slot t is denoted by $P_{BESS}(t)$. And the power consumption of HVDC transmission at time slot t is denoted by $P_{HVDC}(t)$.

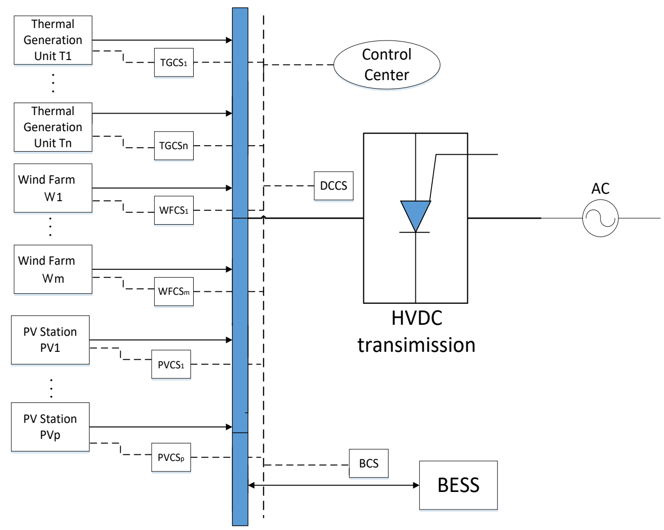


Fig. 1. Electric power system diagram of BESS facilitated hybrid power generation system with DC transmission

The most challenge issue for a hybrid generation system with uncertain renewable energy is frequency stability. The active power fluctuation of renewable generation can cause power imbalance in the sending system, thus threatening system frequency stability. Therefore, an objective function for frequency control is formulized as[19]:

$$\Delta P(t) = P_S(t) - P_L(t) \rightarrow 0 \tag{1}$$

$$P_S(t) = \sum_{i=1}^{n} P_{iT}(t) + \sum_{j=1}^{m} P_{jW}(t) + \sum_{k=1}^{P} P_{kP(t)} \tag{2}$$

$$P_L(t) = P_{BESS}(t) + P_{HVDC}(t) \tag{3}$$

Due to physical constraints, there are both maximum and minimum amount of energy for thermal generations, BESS and HVDC transmission at each time slot,

$$P_{iT}^{\min}(t) \le P_{iT}(t) \le P_{iT}^{\max}(t) \quad \forall t \in \tau \tag{4}$$

$$P_{jW}^{\min}(t) \le P_{jW}(t) \le P_{jW}^{\max}(t) \quad \forall t \in \tau \tag{5}$$

$$P_{kP}^{\min}(t) \le P_{kP}(t) \le P_{kP}^{\max}(t) \quad \forall t \in \tau \tag{6}$$

$$P_{BESS}^{\min}(t) \le P_{BESS}(t) \le P_{BESS}^{\max}(t) \quad \forall t \in \tau \tag{7}$$

$$P_{HVDC}^{\min}(t) \le P_{HVDC}(t) \le P_{HVDC}^{\max}(t) \quad \forall t \in \tau \tag{8}$$

B. *Three- hierarchical Frequency Regulation Scheme*

Since there are interminttent power sources and the renewable power prediction methods are not accurate enough to be applied in power control. We use frequency deviation in the bus line connected with HVDC system as power control indicator. We designed a three-hierarchy power control schem as shown in Fig. 2. In the first level, the bus line frequency deviatio is used as input of the adaptive PI controller, calculating the amount of power adjustment. Then, in level two, the cooperative game model are applied to determine the power adjustment weight factors for each of the two alliance. Alliance group I includes the two uncertainy power sources—wind farms and PV stations. While alliance group II includes other three subsystems—thermal generators, battery energy storage station and HVDC transmission.

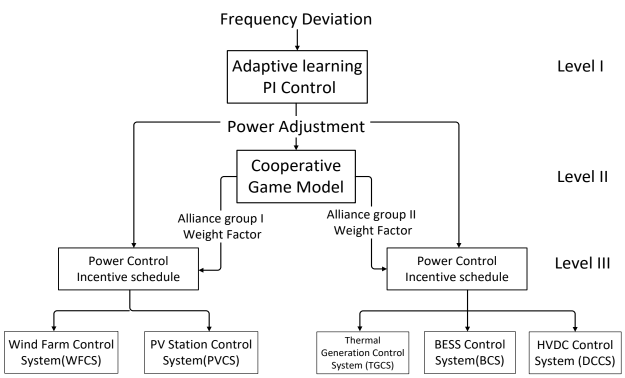


Fig. 2. Three-hierarchy power control scheme

III. ADAPTIVE HIERACHYICAL POWER CONTROL

This section we will specifically introduce how each hierarchies works. Fig. 3 illustrates the specific power control diagram for the hybrid generation HVDC transmission out-sending with BESS.

The three-hierarchy power control system will work out the power output or input of each subsystem, including:

$$P_{PV}(t) = \sum_{i=1}^{p} P_{PVi}(t) + \omega_{PV} \cdot P_{adj} \tag{9}$$

$$P_{WF} = \sum_{j=1}^{m} P_{WFj}(t) + \omega_{WF} \cdot P_{adj} \tag{10}$$

$$P_{TG}^{f2} = \sum_{k=1}^{n} P_{TGk} + \omega_{TG} \cdot P_{adj} \tag{11}$$

$$P_{BESS} = \omega_{BESS} \cdot P_{adj} \tag{12}$$

$$P_{DC} = \omega_{DC} \cdot P_{adj} \tag{13}$$

Since thermal generators have the characteristic of primary frequency regulation. When participating in system power regulation, we not only take advantage of this characteristic but also implement secondary frequency regulation, thus

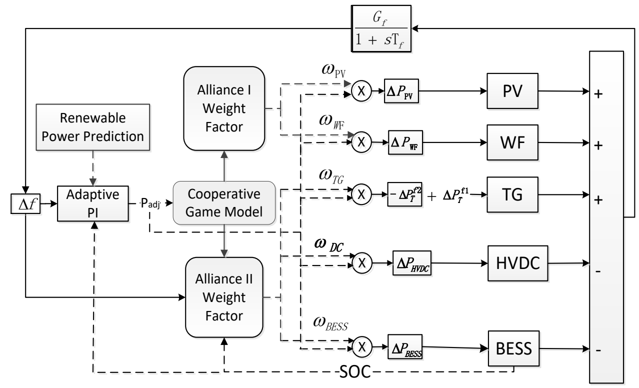


Fig. 3. Power control diagram

$$\Delta P_{iT}(t) = \Delta P_{iT}^{f1}(t) + \Delta P_{iT}^{f2}(t) \tag{14}$$

A. *Adaptive learning PI control*

Through the PI controller, a total active power adjustment order can be obtained. The PI parameters are adaptively improved according to the strategies' ability of resulting a better frequency performance. The purpose of using adaptive framework is to adaptively give preference to appropriate power adjustment on different scenarios of renewable power prediction. The basic idea is to adaptively change PI parameter under different predicted renewable power fluctuation conditions. The dynamic PI controllers should have various proportion and integration according to features of input signal and the demand of SOC reserve. Thus the principle of PI control adaptive learning is

- For power deviation much higher than average (schedule time interval is 15 minutes), the advanced control should enable less SOC in order to schedule enough capacity to absorb spare renewable power.
- For power deviation much lower than average (schedule time interval is 15 minutes), the advanced control should enable more SOC in order to schedule enough capacity to offset decreased renewable power.
- For peak or valley shape like power fluctuation that has the feature of large and fast but small time interval, the proportion should be larger.

According to above principle the following rule is used to update the PI control parameters:

TABLE I. PROCEDURE OF ADAPTIVE LEARNING PI CONTROL

Adaptive learning PI control
Step (0) Initialization
The initialized PI parameter P_{pi}^0, I_{pi}^0 is set according to 2 hours ultra-short term power prediction. Set initial time t=0, time interval $\varepsilon = 15$

time slots (15 minutes). The initial parameters are function of predicted maximum and minimum renewable power in two hours.

$$P_{pi}^{0}(t) = f(\max\{\tilde{P}_{RG}(\tau)\}, \min\{\tilde{P}_{RG}(\tau)\}) \quad \tau = (t, \dots, t+\varepsilon)$$
$$I_{pi}^{0}(t) = g(\max\{\tilde{P}_{RG}(\tau)\}, \min\{\tilde{P}_{RG}(\tau)\}) \quad \tau = (t, \dots, t+\varepsilon)$$

Calculate the average prediction value of the 2 hours interval $\tilde{P}_{RG}^{avg}$

Step (1)

If $D_1 = \sum_{\tau=t}^{t+\varepsilon} (\tilde{P}_{RG}^{avg} - \tilde{P}_{RG}(\tau)) > 0.1 \cdot \tilde{P}_{RG}^{avg}$

$$P_{pi}(\tau) = P_{pi}^{0}(t) - k_{11} D_1 \Delta f(\tau) \quad \tau = (t, \dots, t+\varepsilon)$$
$$I_{pi}(\tau) = I_{pi}^{0}(t) - k_{12} D_1 \Delta f(\tau) \quad \tau = (t, \dots, t+\varepsilon)$$

else if $D_1 = \sum_{\tau=t}^{t+\varepsilon} (\tilde{P}_{RG}^{avg} - \tilde{P}_{RG}(\tau)) < -0.1 \cdot \tilde{P}_{RG}^{avg}$

$$P_{pi}(\tau) = P_{pi}^{0}(t) - k_{21} D_1 \Delta f(\tau) \quad \tau = (t, \dots, t+\varepsilon)$$
$$I_{pi}(\tau) = I_{pi}^{0}(t) - k_{22} D_1 \Delta f(\tau) \quad \tau = (t, \dots, t+\varepsilon)$$

end if

Set $t = t + \varepsilon$

Step (2) If t <120, go to step (1), otherwise go to step (0).

In the adaptive learning process two time-dimension prediction are used, the longer time scale is 4 hours and the shorter time scale is 15 minutes. The ultra-short term prediction time scale is 2 hours, and the prediction will be updated every 15 minutes.

B. *Coopeprative Approach for hybrid generation system afflicated by BESS with HVDC sending*

In such complicated hybrid generation system, in order to fulfill optimal benefit of the whole system we propose a game theory based cooperative approach. The cooperative approach can decide the adjustment weight factors for each of the two alliance.

There are five participators, including wind farm (WF) generations, photovoltaic (PV) generations, thermal generations (TG), battery energy storage station (BESS) and HVDC. Since PV and WG are uncertain power generation, although there are total 16 alliance combinations for cooperative game with five participators, we choose the following alliance combination:

[{PV, WG}, {TG, BESS, HVDC}]

The weight factor strategy of each subsystem is denoted as

$\omega_{WG} \in [0,1]$, $\omega_{PV} \in [0,1]$, $\omega_{TG} \in [0,1]$, $\omega_{BESS} \in [0,1]$, $\omega_{HVDC} \in [0,1]$ and

$$\omega_{WG} + \omega_{PV} + \omega_{TG} + \omega_{BESS} + \omega_{HVDC} = 1 \tag{15}$$

The strategy's continuous spaces are

$$\omega_{WG}\Delta P_{adj}(t) \in \{S_{WG} = [\Delta P_{WG}^{min}(t), \Delta P_{WG}^{max}(t)]\} \tag{16}$$

$$\omega_{PV}\Delta P_{adj}(t) \in \{S_{PV} = [\Delta P_{PV}^{min}(t), \Delta P_{PV}^{max}(t)]\} \tag{17}$$

$$\omega_{TG}\Delta P_{adj}(t) \in \{S_{TG} = [\Delta P_{TG}^{min}(t), \Delta P_{TG}^{max}(t)]\} \tag{18}$$

$$\omega_{BESS}\Delta P_{adj}(t) \in \{S_{BESS} = [\Delta P_{BESS}^{min}(t), \Delta P_{BESS}^{max}(t)]\} \tag{19}$$

$$\omega_{HVDC}\Delta P_{adj}(t) \in \{S_{HVDC} = [\Delta P_{HVDC}^{min}(t), \Delta P_{HVDC}^{max}(t)]\} \tag{20}$$

For participators {PV, WG}, {TG, BESS, HVDC}, the strategy sets are

$$S_{WP} = [\Delta P_{WG}^{min}(t), \Delta P_{WG}^{max}(t); \Delta P_{PV}^{min}(t), \Delta P_{PV}^{max}(t)];$$

$$S_{BTH} = [\Delta P_{BESS}^{min}(t), \Delta P_{BESS}^{max}(t); \Delta P_{HVDC}^{min}(t), \Delta P_{HVDC}^{max}(t); \Delta P_{TG}^{min}(t), \Delta P_{TG}^{max}(t)]$$

and the information sets $v(t)$, $I(t)$, $SOC(t)$ and Δf separately represent wind speed, solar irradiance, state of charging of the BESS and frequency of sending system.

The system operator's objective is to minimize the power fluctuation so as to minimize frequency fluctuation, as presented in (1). Therefore, under the constraint of power fluctuation control as presented in (11), the payoff function

$$G_{WP}(\Delta P_{WG}, \Delta P_{PV}, \Delta P_{BESS}, \Delta P_{TG}, \Delta P_{HVDC})$$

$$G_{BTH}(\Delta P_{WG}, \Delta P_{PV}, \Delta P_{BESS}, \Delta P_{TG}, \Delta P_{HVDC})$$

are respective wind-solar alliance payoff and BESS-thermal-HVDC alliance payoff. The payoff is calculated by

$$G(t) = G_{s1}^{E}(t) + G_{ser}^{BESS}(t) + G_{sub}(t) - C_{M}(t) \tag{21}$$

in which $G_{s1}^{E}(t)$ is the electricity power sale profit (sale price included the government subsidy), $G_{ser}^{BESS}(t)$ is the profit from using BESS for facilitate services, $G_{sub}(t)$ is government subsidy, and $C_{M}(t)$ is operating cost.

As for alliance {PV, WG}, the payoff is calculated by

$$G_{PVWG}(t) = G_{s1}^{E,WP}(t) + G_{sub}^{WP}(t) - C_{M}^{WP}(t) \tag{22}$$

and for alliance {TG, BESS, HVDC}, the payoff is calculated by

$$G_{BTH}(t) = G_{s1}^{E,BTH}(t) + G_{sub}^{BTH}(t) - C_{M}^{BTH}(t) \tag{23}$$

If this cooperative game model has the Nash Equilibrium point $\{\Delta P'_{WG*} + \Delta P'_{PV*}\}$ and $\{\Delta P'_{BESS*} + \Delta P'_{TG*} + \Delta P'_{HVDC*}\}$, it should be the optimal strategy as the other has the optimized strategy, that reaches the Nash equilibrium maximum payoff strategy under this game alliance.

C. *Alliance Weight Factors*

1) Weight factor in Wind farm and PV station alliance

We distribute power adjustment weight factor in wind-solar alliance according to their operation capacity, which are also a dynamic value. In practical operation, the wind generation can be regulated to both increase and decrease, while the solar generation can only be regulated to decrease. Thus, the weight factors for wind farm and PV station are formulated as:

$$\omega_{WG}(t) = \begin{cases} \omega_{WGPV} \cdot \dfrac{\sum_{j=1}^{m} C_{WGj}(t)}{\sum_{j=1}^{m} C_{WGj}(t) + \sum_{k=1}^{p} C_{PVk}(t)} & \Delta f > 0 \\ \omega_{WGPV} & \Delta f < 0 \end{cases} \tag{24}$$

$$\omega_{PV}(t) = \begin{cases} \omega_{WGPV} \cdot \dfrac{\sum_{k=1}^{p} C_{PVk}(t)}{\sum_{j=1}^{m} C_{WGj}(t) + \sum_{k=1}^{p} C_{PVk}(t)} & \Delta f > 0 \\ 0 & \Delta f < 0 \end{cases} \quad (25)$$

in which $C_{WGj}(t)$ and $C_{PVk}(t)$ are operation capacity of each wind farm and PV station.

2) Weight factor in alliance of thermal units, BESS and HVDC transmission

Equilibrium point $\{\Delta P'_{BESS*} + \Delta P'_{TG*} + \Delta P'_{HVDC*}\}$ is corresponding to $\omega_{BTH} = \omega_{TG} + \omega_{BESS} + \omega_{HVDC}$. For the power adjustment weight factor distribution in BESS-thermal-HVDC alliance, considering secondary frequency regulation is normally decided by regional AGC (autonomous generation control), which should be considered as a constant in this paper research time interval. Thus the thermal power weight factor is

$$\omega_{TG} = \omega_{TG}^{0} \quad (26)$$

Then the total power adjustment weight factor of BESS and HVDC should be

$$\omega_{BESS} + \omega_{HVDC} = \omega_{BH} = \omega_{BTH} - \omega_{TG}^{0} \quad (27)$$

Since in the first level we propose to take advantage of renewable power prediction, the BESS was priori in small amount of frequency deviation regulation (range in ±0.1Hz). Considering economic benefits and operation stability, the weight factor distribution at larger frequency deviation should depend on SOC of BESS. The following table I shows how weight factors of BESS and HVDC should be attributed according to the principles that HVDC power order should less frequently than BESS and to be more profitable when battery SOC at suitable condition BESS undertaking more power adjustment. In case 2,4,5,7 BESS and HVDC can work in cooperative way, while in case 1,3,6,8 BESS and HVDC are competitive.

TABLE II. BESS AND HVDC WEIGHT FACTORS ADJUST PRINCIPLE

SOC	Δf (Hz)	BESS	HVDC	Case
SOC<0.4	$\triangle f$>0.2	charge↑ ω_{BESS}↑	ω_{HVDC}↑	1
	0.1<$\triangle f$<=0.2	charge↑ ω_{BESS}↑	ω_{HVDC}↓	2
	-0.2<=$\triangle f$<-0.1	discharge↓ ω_{BESS}↓	ω_{HVDC}↓	3
	$\triangle f$<-0.2	discharge↓ ω_{BESS}↓	ω_{HVDC}↑	4
0.4<=SOC<=0.6 Or -0.1<= $\triangle f$<=0.1		$\omega_{BESS} = \omega_{BTH} - \omega_{TG}$	ω_{HVDC} = 0	——
SOC>0.6	$\triangle f$>0.2	charge↓ ω_{BESS}↓	ω_{HVDC}↑	5
	0.1<$\triangle f$<=0.2	charge↓ ω_{BESS}↓	ω_{HVDC}↓	6
	-0.2<=$\triangle f$<-0.1	discharge↑ ω_{BESS}↑	ω_{HVDC}↓	7
	$\triangle f$<-0.2	discharge↑ ω_{BESS}↑	ω_{HVDC}↑	8

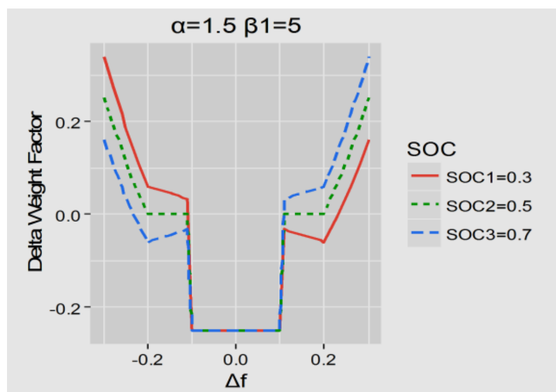
Here we define a weight factor coefficient σ_{ω}^{BH} as

$$\omega_{HVDC} = \frac{\omega_{BH}}{2} + \sigma_{\omega}^{SOC,f} \quad (28)$$

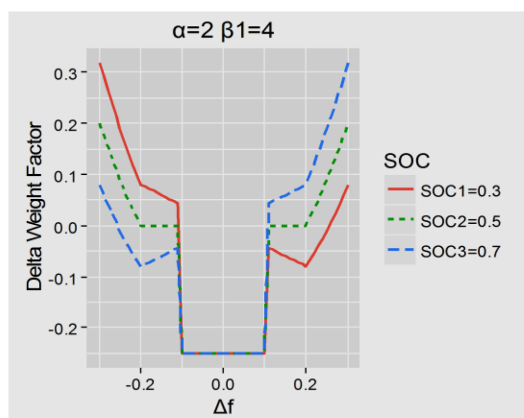
$$\omega_{HVDC} = \frac{\omega_{BH}}{2} - \sigma_{\omega}^{SOC,f} \quad (29)$$

$$\sigma_{\omega}^{BH} = \begin{cases} -\dfrac{\omega_{BH}}{2} & 0.4 \le SOC \le 0.6 \,||\, -0.1 \le \Delta f \le 0.1 \\ \alpha(SOC-0.5)\cdot\Delta f & 0.1 < \Delta f \le 0.2 \,||\, -0.2 \le \Delta f < 0.1 \\ \beta(\Delta f^2 - 0.04) + \alpha(SOC-0.5)\cdot\Delta f & \Delta f < -0.2 \,||\, \Delta f > 0.2 \end{cases} \quad (30)$$

Since there are both cooperative and competitive case in the alliance, the coefficient α, β is dynamic according to self-adaptive learning process. The self-adaptive learning is to change α and β based on previous operation effects and cost. Thus we need to find a balance between power control results and alliance operating benefits. Through change alliance award to BESS and HVDC, it can make HCS and BCS change the adjustment rate. Fig. 4 illustrate examples how the value of σ_{ω}^{BH} changes in different α, β setting.



(a) α =1.5, β =5



(b) α =2, β =6.

Fig. 4. Weight factor variable (a) α =1.5, β =5 (b) α =2, β =6.

IV. Performance Simulation

A. *Case model*

We build a model to demonstrate the power adjustment method that based on game theory of weight factor can effectively implemented in system of the renewable power generation with HVDC out-sending facilitated by BESS.

As in the PI adaptive control, the renewable power prediction value will be used to adaptively recalculate the proportion and integration parameters. This paper considers a 15% error prediction scenario, and the prediction curve and practical curve are shown in Fig. 5.

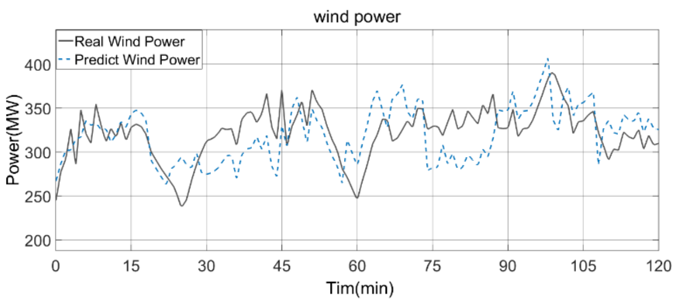


Fig. 5. Predicted and Practical Wind Power

For the BESS and HVDC weight factor coefficient $\sigma_{\omega}^{\mathrm{BH}}$, we make a simulation for the case that $\alpha=1.5$, $\beta=5$.

The HVDC nominal transmission power is 800MW, while the thermal power and renewable power ratio is closed to 1:1. The power capacity of BESS is 25MWh, which can keep work 15 minutes in maximum power 100MW.

B. *Results*

The section will illustrate the simulation result for the case presented above. As we use the practical and predicted renewable power shown in Fig. 5, under three-levels adaptive power control, the battery energy storage station power, HVDC transmitting power and thermal power are correspondingly shown in Fig. 6-Fig. 8.

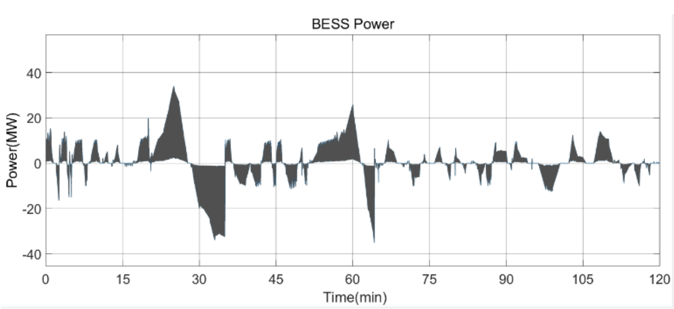


Fig. 6. Battery Energy Storage Station Power

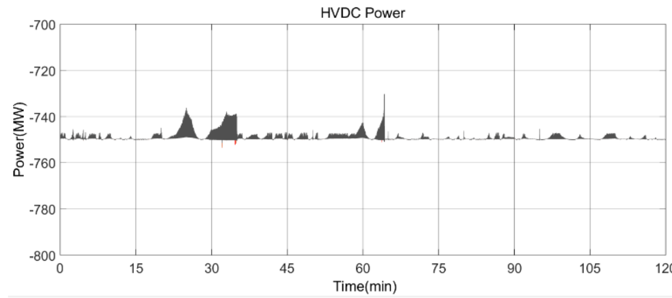


Fig. 7. HVDC Transmitting Power

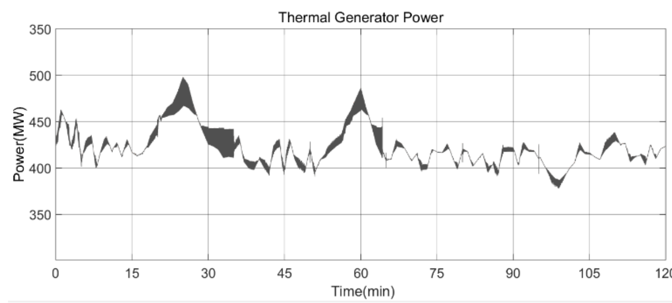


Fig. 8. Thermal Generation Power

The adaptive PI control in the top hierarchy send the power adjustment order to each alliance as shown in figure 9. Alliances BESS and HVDC undertake most frequency regulation task, which could enable more renewable power integrated into system.

To demonstrate the adopting the adaptive PI control enables the hybrid generation system with HVDC transmission facilitated by BESS have better frequency performance and is more economic, we make the comparison between adaptive PI control and constant PI control. The SOC and performance of power system frequency with adaptive Pi and without adaptive are shown in Fig. 10 and Fig. 11.

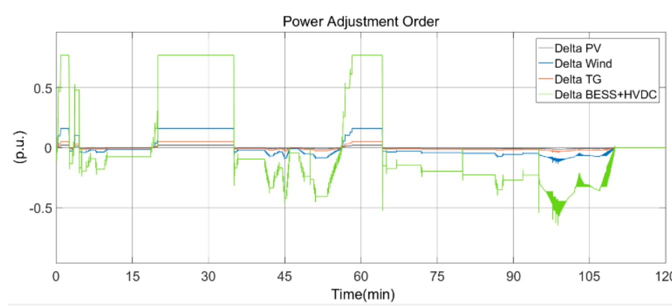


Fig. 9. Alliance Power Adjustment Order

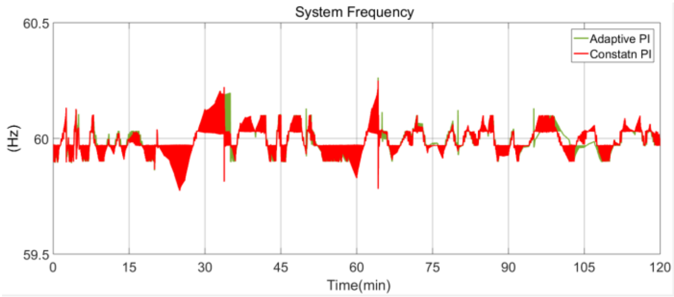


Fig. 10. System Frequency

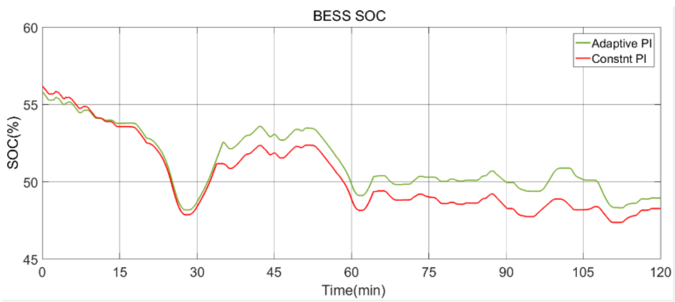


Fig. 11. SOC of Battery Energy Storage Station

As illustrated in Fig.10 and Fig 11, the adaptive hierarchical power control can efficiently regulate power imbalance. The adaptive PI control in the top level will lead to a better performance of system frequency. The SOC curve of adaptive control remains closer to healthy state, in which range the battery energy storage station operating more cost efficiently.

V. CONDLUSION

This paper uses battery energy storage station to help solve frequency stability problem in large-scale uncertainty renewable power with HVDC out-sending system. We propose the hierarchical based power control strategy to adaptively update control parameter in each level. From the top to bottom level, the dynamic process includes adaptive learning PI controller, game based alliance weight factors and self-adaptive rules for alliance weight factor distribution. Finally, based on the designed control strategy we made a simulation model, in which the selected alliance weight factors are used. The simulation result has testified that the hierarchical adaptive learning process can improve system frequency performance and help battery energy storage station operate in the more economic status.

REFERENCES

[1] Y. Zhongping et al., "Integrated wind and solar power forecasting in China," Service Operations and Logistics, and Informatics (SOLI), 2013 IEEE International Conference on, Dongguan, 2013, pp. 500-505.

[2] P. Huang, S. O. Negro, M. P. Hekkert, K. Bi, "How China became a leader in solar PV: An innovation system analysis," Renewable and Sustainable Energy Reviews, vol. 64, pp. 777-789, October 2016.

[3] L. Li and Z. Sun, "Dynamic Energy Control for Energy Efficiency Improvement of Sustainable Manufacturing Systems Using Markov Decision Process," in IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 43, no. 5, pp. 1195-1205, Sept. 2013.

[4] L. Zheng, Q. Zhang, "Study on the development mode of national grid of China, " Proceedings of the CSEE, vol 7, pp. 1-10+25, March 2013.

[5] L. Zheng, Q.Zhang and C. Dong, "Efficient and security transmission of wind, photovoltaic and thermal power of large-scale energy resource bases through UHVDC projects," Proceedings of the CSEE, vol 16, pp. 2513-2522, June 2014.

[6] X. Zhao, S. Li and S. Zhang, "The effectiveness of China's wind power policy: An empirical analysis," Energy Policy, vol 95, pp. 269-279, August 2016.

[7] M. Yoon, Y.-T Yoon, G. Jang, "A Study on Maximum Wind Power Penetration Limit in Island Power System Considering High-Voltage Direct Current Interconnections," Energies, vol 8, pp. 14244-14259, December 2015.

[8] Y. Chen, D. Chen, S. Ma, "Studies on High-Frequency Generator Tripping Strategy for Wind-Photovoltaic-Thermal-Bundled Power Transmitted by AC/DC System," Power System Technology, vol 40, pp. 186-192, January 2016.

[9] P. Wu, S. Xu, and B. Chao, "Research of weak sending-end coupling characteristics for bundled wind-thermal power transmission of UHVDC project," Electric Power Automation Equipment, vol 36, pp. 60-66, January 2016.

[10] M. Li, X. Zhang, X. Chang, "Research on power modulation applied in wind-thermal bundled islanded DC transmission," Electric measurement and instrumentation, vol 53, pp. 109-112+123, March 2016.

[11] C. M. Cheng, S. L. Tsao and P. Y. Lin, "SEEDS: A Solar-Based Energy-Efficient Distributed Server Farm," in IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 45, no. 1, pp. 143-156, Jan. 2015.

[12] A. Zhang, S. Li, C. Zhang, "Voltage and Frequency Control of Wind-thermal-bundled Island Transmission by UHVDC System," Proceedings of the CSU-EPSA, vol 23, pp. 29-35, March 2015.

[13] A. Scacchioli, G. Rizzoni, M. A. Salman, W. Li, S. Onori and X. Zhang, "Model-based Diagnosis of an Automotive Electric Power Generation and Storage System," in IEEE Transactions on Systems, Man, and Cybernetics: Systems, vol. 44, no. 1, pp. 72-85, Jan. 2014.

[14] N. Saadat, S. S. Choi and D. M. Vilathgamuwa, "A Statistical Evaluation of the Capability of Distributed Renewable Generator-Energy-Storage System in Providing Load Low-Voltage Ride-Through," in IEEE Transactions on Power Delivery, vol. 30, no. 3, pp. 1128-1136, June 2015.

[15] X. Ke, N. Lu and C. Jin, "Control and Size Energy Storage Systems for Managing Energy Imbalance of Variable Generation Resources," in IEEE Transactions on Sustainable Energy, vol. 6, no. 1, pp. 70-78, Jan. 2015.

[16] Li Xiangjun, Hui Dong, and Lai Xiaokang (2013). Battery Energy Storage Station (BESS)-Based Smoothing Control of Photovoltaic (PV) and Wind Power Generation Fluctuations. IEEE Transactions on Sustainable Energy, Vol. 4, No 2, pp.464-473, Apr.2013.

[17] K. Tarvainen and Y. Y. Haimes, "Coordination of Hierarchical Multiobjective Systems: Theory and Methodology," in IEEE Transactions on Systems, Man, and Cybernetics, vol. 12, no. 6, pp. 751-764, Nov. 1982.

[18] Q. D. Lã, Y. H. Chew, B-H Soong. *Potential Game Theory*, Springer International Publishing, Switzerland, 2016.

[19] X. Li, Y-J. Song, S-B. Han, “Frequency control in micro-grid power system combined with electrolyzer system and fuzzy PI controller,“ Journal of Power Sources, vol 180, pp. 468-475, May 2008.